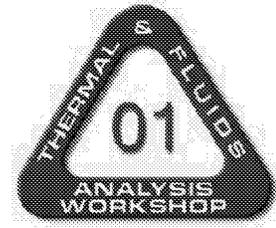


COMPARISON OF ANALYTICAL AND NUMERICAL PERFORMANCE PREDICTIONS FOR AN INTERNATIONAL SPACE STATION NODE 3 INTERNAL ACTIVE THERMAL CONTROL SYSTEM REGENERATIVE HEAT EXCHANGER



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ABSTRACT

The complexity of International Space Station (ISS) systems modeling often necessitates the concurrence of various dissimilar, parallel analysis techniques to validate modeling. This was the case with a feasibility and performance study of the ISS Node 3 Regenerative Heat Exchanger (RHX). A thermo-hydraulic network model was created and analyzed in SINDA/FLUINT. A less complex, closed form solution of the systems dynamics was created using an Excel Spreadsheet. The purpose of this paper is to provide a brief description of the modeling processes utilized, the results and benefits of each to the ISS Node 3 RHX study.

INTRODUCTION

Node 3 enhances the ISS stand-alone (without orbiter) crew capacity from a maximum of three to a maximum of seven by providing dedicated utilities supporting crew habitability functions at Station level. Of these dedicated utilities, the most critical are the Environmental Control and Life Support System (ECLSS) racks which condition the internal atmosphere. To provide for continuous operation, the Node 3 Thermal Control System (TCS) Low Temperature Loop (LTL) and Moderate Temperature Loop (MTL) collect and reject waste heat from the ECLSS racks. Requirements exist to ensure that during a single failure of the External Active Control System (EATCS) Loop B (LTL heat rejection capability) or power domain 2/3 (LTL equipment power) TCS function would continue to provide cooling to the critical ECLSS racks. In order to sustain operation for this contingency case the nominally dual loop mode TCS must accommodate a Loop Crossover Assembly (LCA) to allow the two loops to operate as one in series, utilizing the MTL to provide coolant for LTL heat rejection.

ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEM (ECLSS)
DESCRIPTION

The Environmental Control and Life Support Systems (ECLSS) controls the atmosphere of the internal pressurized volume in terms of air pressure, temperature, humidity, particulate and microbial concentrations, and velocity. Additionally, the ECLSS racks provide for crew waste management and hygiene. The following rack assemblies achieve these ECLSS functions:

- Atmosphere Revitalization System (ARS) rack
 - Sample Delivery System (SDS) – to allow proper air flow distribution inside the rack
 - Trace Contaminant Control Subassembly (TCCS) – processes the cabin air to remove the gaseous trace contaminants that could be hazardous for the crew
 - Major Constituent Analyzer (MCA) – continuously monitors the partial pressures of the major atmospheric constituents in the Node 3 cabin and from other modules of the ISS.
 - Area smoke detection and fire indication
 - Carbon Dioxide Removal Assembly (CDRA) – processes the cabin air to remove carbon dioxide
 - Avionics Air Assembly (AAA) – provides air circulation for fire detection and provides air cooling for rack components
- Oxygen Generation System (OGS) rack – Contains the Oxygen Generator Assembly (OGA) to produce oxygen for atmospheric supply
- Water Recovery System (WRS) #1 & #2 racks – Waste water processing to potable water and pre-treated urine to urine distillate processing
- Waste & Hygiene Compartment (W&HC) #1 & #2 racks – Crew personal hygiene and crew urine and fecal collection
- Common Cabin Air Assembly (CCAA) – Air/Water Heat Exchanger (HX) that transfers environmental heat loads to the LTL for rejection

NODE 3 INTERNAL ACTIVE THERMAL CONTROL SYSTEM (IATCS)
DESCRIPTION - NOMINAL OPERATION

The Node 3 Internal Active Thermal Control System (IATCS) consists of two loops that employ single-phase water as a heat transport fluid: the Node 3 Low Temperature Loop (LTL) and the Node 3 Moderate Temperature Loop (MTL). The Node 3 LTL and MTL collect and transport waste heat from the subsystems avionics equipment, the environmental control system and from subsystems and payloads within elements attached to Node 3.

The collected heat load is rejected by means of two separate single-phase ammonia loops A and B, via two dedicated NH₃/H₂O Heat Exchangers (HX), mounted on the external shell of the Node 3 Zenith Cone. The collected heat is transferred from the ammonia loops to the Station radiators for rejection.

Each loop contains various components that provide pressure and temperature control. The functional diagram of the Node 3 IATCS is depicted in Figure 1.

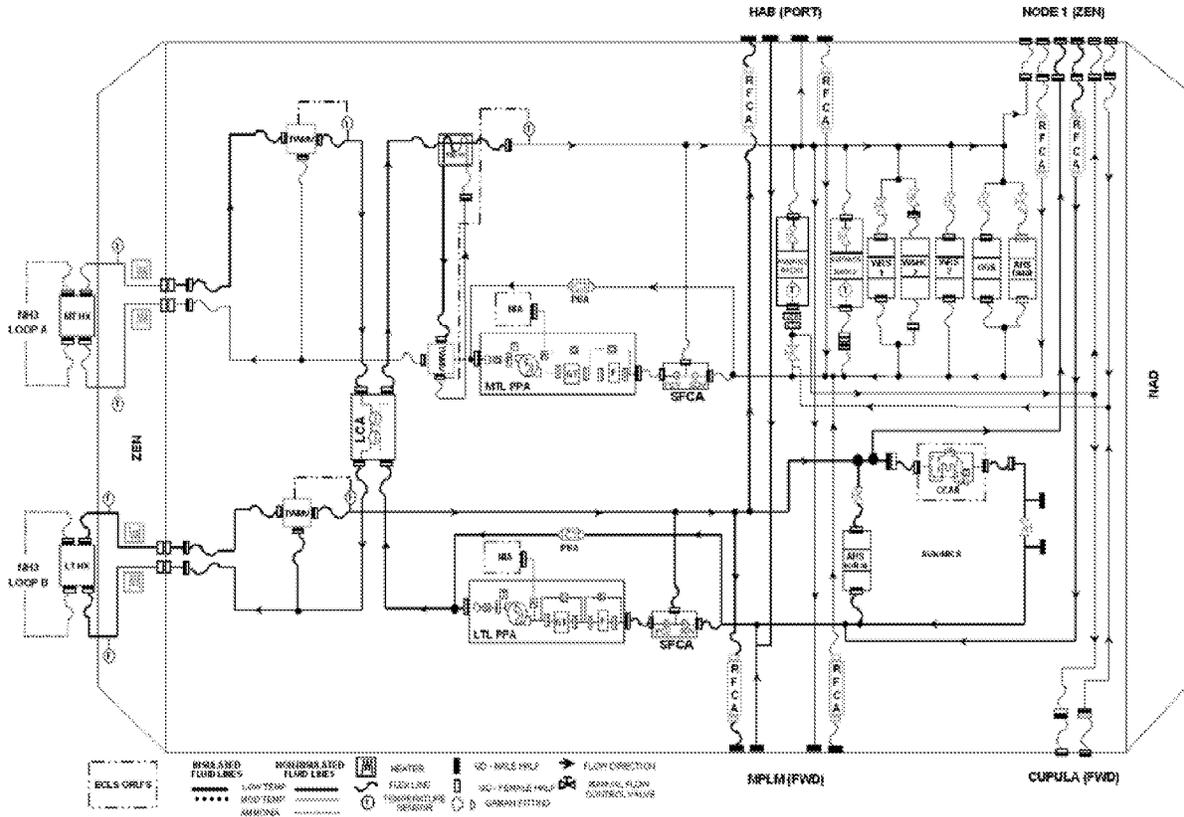


Figure 1 – Node 3 IATCS

LOW TEMPERATURE LOOP (LTL)

At a non-selectable temperature range from 38° – 43°F, the LTL guarantees the correct flow rate distribution and removes waste heat from the attached modules Multi-Purpose Logistics Module (MPLM), Node 1 and Habitation Module (HAB) LT loop, the ECLSS CCAA, the ARS – CDRA rack, and the internal Cold Plate HXs located on the external side of the Zenith cone shell.

MODERATE TEMPERATURE LOOP (MTL)

At a non-selectable temperature range from 61° - 65°F, the Moderate Temperature Loop (MTL) guarantees the correct flow rate distribution and removes waste heat from the attached Modules MPLM scar, Node 1 MT & High Temperature (HT) loop and Cupola, the ARS – AAA rack, WRS-#1 & -#2, W&HC-#1 & -#2, OGS – OGA rack and Cold Plate cooled electronic equipment located in Avionics Racks #1 & #2.

NODE 3 INTERNAL ACTIVE THERMAL CONTROL SYSTEM (IATCS) DESCRIPTION - CONTINGENCY OPERATION

A single failure of the EATCS loop B or power domain 2/3 would result in the loss of LTL coolant flow, creating a condition where CO₂ removal capability would be lost in both the United States Laboratory (USL) module and Node 3. To combat this Node 3 TCS will accommodate a LCA to connect the two loops in series to operate as a single loop, utilizing the MTL to provide coolant for LTL heat rejection.

In view of the fact that the MTL will be providing coolant for LTL use, the temperature of the MTL transport fluid must be adjusted to match the need of the equipment on the LTL. This is accomplished by adjusting the set point of the MTL Common Thermal Bus (CTB) Three Way Mix Valve (TWMV) from 65.0°F (MTL nominal) to 50.0°F. Consequently, as the transport fluid re-enters the MTL, the LTL equipment heat load may not have been enough as to raise the fluid above the dew point (65.0°F). Therefore, the system ensures the fluid temperature is raised above the dew point with a RHX in conjunction with a TWMV (65.0°F set point) to preclude condensation upon the MTL coolant lines and equipment.

REGENERATIVE HEAT EXCHANGER (RHX) FEASIBILITY AND PERFORMANCE

As previously stated, the RHX must ensure the temperature of the MTL fluid is above the dew point to preclude condensation. A study was made to determine if the condensation preclusion requirement could be met under a “low load” scenario (no attached modules). The scope of this case is based on estimated heat dissipation values ascertained from the Node 3 Design Review Thermal Budget¹. The estimated values were derived from the equipment that were considered to be operational after a single failure of the EATCS loop B power domain 2/3. The heat loads utilized for the analysis are shown in Table 1. The analysis also shows the allowable performance envelope for condensation preclusion and heat rejection.

CLOSED FORM SOLUTION

A closed form solution was developed to ascertain RHX performance based on Node 3 single loop mode architecture. Figure 2 shows the layout and nomenclature used for the closed form solution.

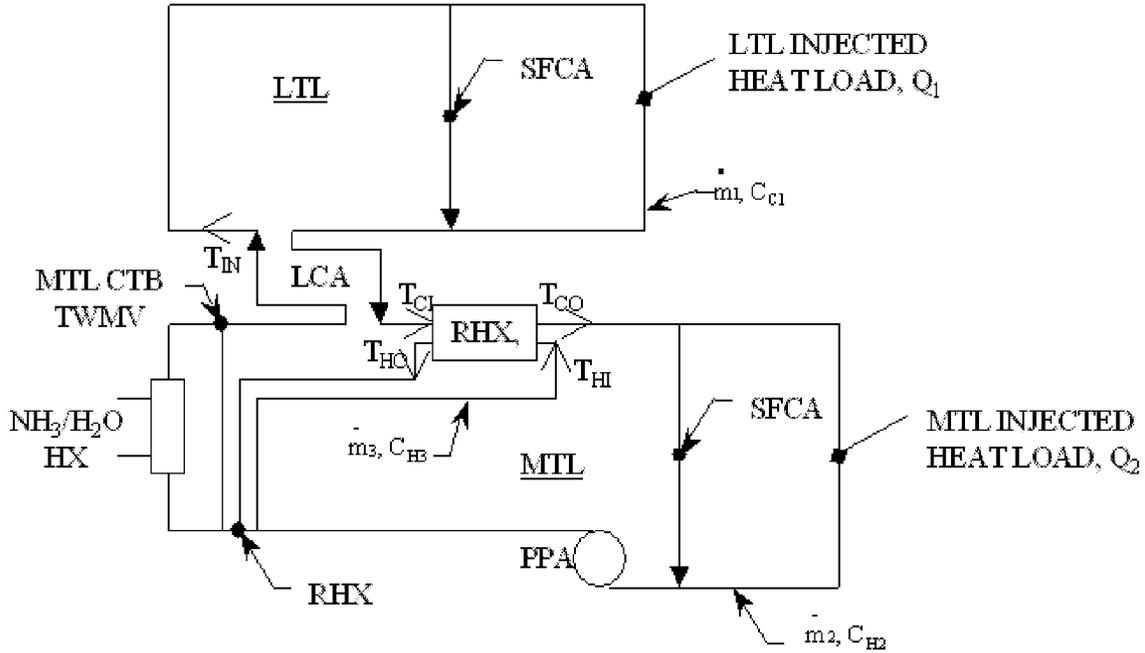


Figure 2 – Closed Form Solution Schematic

The Pump Package Assembly (PPA) total flowrate considered in the calculation was 2300 lbm/hr due to single loop mode pump performance degradation from the nominal 3000 lbm/hr. MIL Common Thermal Bus (CTB) Three Way Mix Valve (TWMV) temperature set point (T_{IN}) was changed from 65.0°F (MIL nominal) to 50.0°F, and the RHX TWMV outlet temperature (T_{CO}) was set to 65.0°F to avoid condensation. The knowns, LTL and MIL (Q_1 and Q_2) injected heat loads and RHX hot side flowrate (\dot{m}_3) were varied in the analysis to ascertain the useful working envelope for the system. T_{CO} and T_{IN} were also specified in the study. Assumptions made include the following; H_2O constant specific heat, $c_p = 1.0$ Btu/lbm°F, $C_{MIN} = C_{H3} = \dot{m}_3 c_p$, and $C_{H2} = C_{C1} = 2300$ Btu/hr°F.

As shown in Figure 3², linear interpolation about a cold side water flowrate of 2300 lbm/hr yields an equation for the RHX hot side effectiveness of:

Effectiveness equation:
$$\epsilon \approx \left(\frac{-0.28}{1500} \right) (\dot{m}_3 - 1500) + 0.93 \tag{i}$$

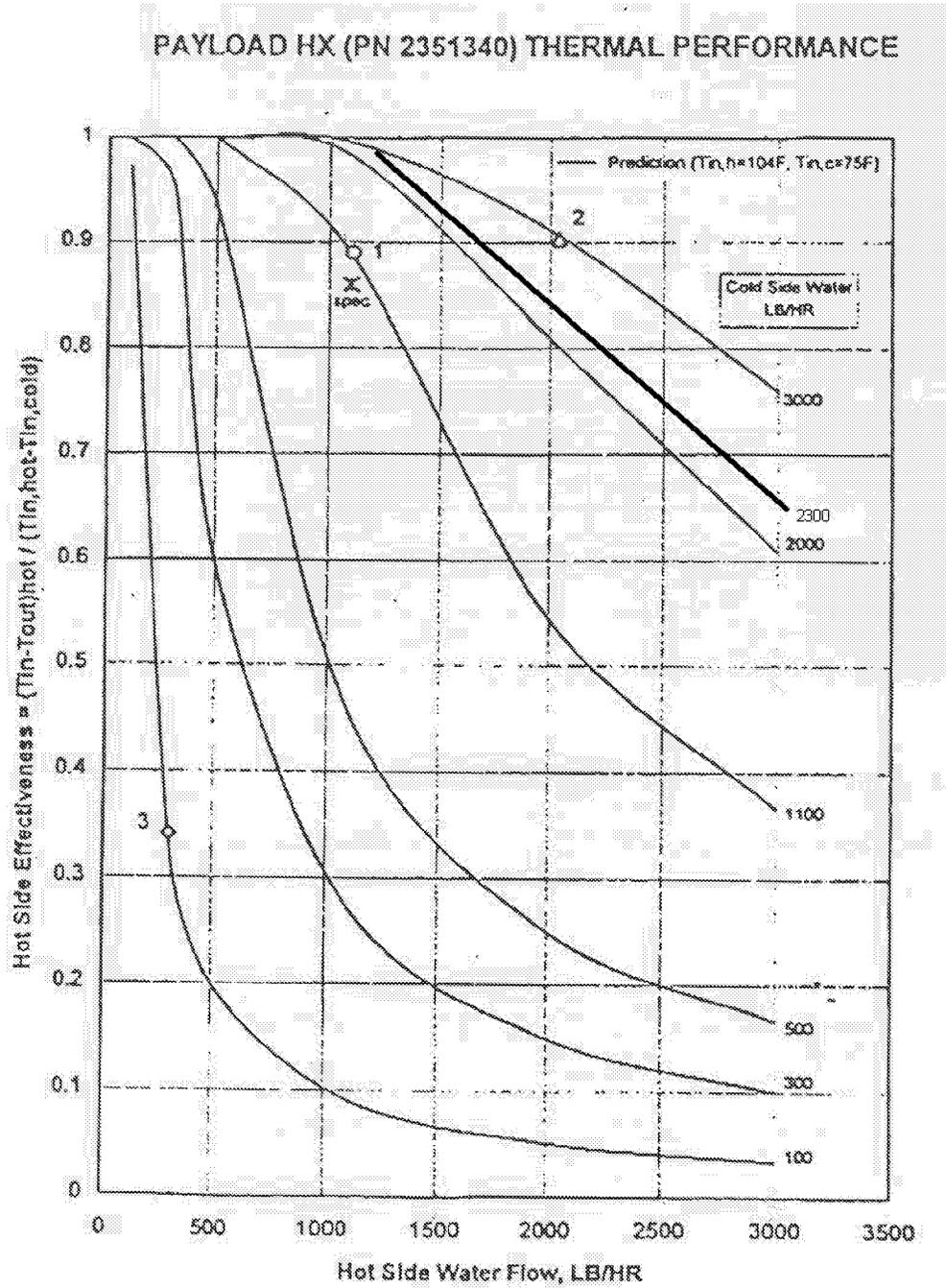


Figure 3 – Regenerative Heat Exchanger Performance Curves

The following relationships³ are appropriate for the effectiveness - NTU method of heat exchanger analysis.

$$Q_{MAX} = Q_T / \varepsilon \quad (2)$$

$$T_{CI} = T_{IN} + Q_1 / C_{C1} \quad (3)$$

$$T_{CI} = -Q_{MAX} / C_{MIN} + T_{HI} \quad (4)$$

$$T_{HI} = T_{CO} + Q_2 / C_{H2} \quad (5)$$

$$T_{CO} = T_{CI} + Q_T / C_{C1} \quad (6)$$

$$Q_T = \varepsilon(C_{MIN})(T_{HI} - T_{CI}) \quad (7)$$

Combining equations. 1-7 and solving for \dot{m}_3 in terms of Q_1 , Q_2 , T_{CO} , and T_{IN} with assumptions 1-3 yields:

$$\dot{m}_3 = \frac{-1347.92 \left\{ \left[- (Q_1 + 5.78(Q_2 - 397.81(T_{CO} - T_{IN}))) \right]^{1/2} - 2.41 \left[Q_1 - Q_2 - 2300(T_{CO} - T_{IN}) \right]^{1/2} \right\}}{\left[Q_1 - Q_2 - 2300(T_{CO} - T_{IN}) \right]^{1/2}}$$

With the aforementioned relationships, an Excel Spreadsheet was developed to perform trade studies for the system. With the Excel “solver” function, it was possible to determine either flow rates or heat loads necessary for the system to operate successfully. Table 1 gives the thermal loads associated with the various components and Figure 4 shows the input interface to the Excel Spreadsheet.

SOURCE OR COMPONENT	THERMAL LOAD [Watts]		
	LIL	MIL	
ARS / CDRA	725.0	-	
ARS / AAA	-	229.0	
OGA	-	2320.0	
MIL PPA	-	470.0	
TMMV	-	1.0	
SECA	-	2.0	
Cold biased altitude producing a negative environmental heat load with cabin air temperature at 80°F	*720.0	-	
2 crew members	*270.0	-	
Avionics Packs #1	*17.3	557.7	
CCAA Water Separator	*44.7	-	
CCAA Temp. Control Valve	*1.0	-	
CCAA EIB	*6.5	-	
Air Smoke Detect (ASD)	*6.0	-	
Harness	*20.0	-	
THC Cabin Fan	*191.0	-	
General Luminary Assy.	*300.0	-	
ELPS	*10.0	-	
UOP - 1, 2, 3, & 4	*36.0	-	
Pressure Control Panel	*20.0	-	
Nitrogen Introduction Assy	*14.4	-	
IMV Fan	*110.0	-	
IMV Valve	*4.0	-	
PCS	*100.0	-	
CCAA	430.9	-	
	TOTALS	1155.9	3579.7

* - Air Load total value incorporated for CCAA

Table 1 – Single Loop Mode Thermal Budget (est.)

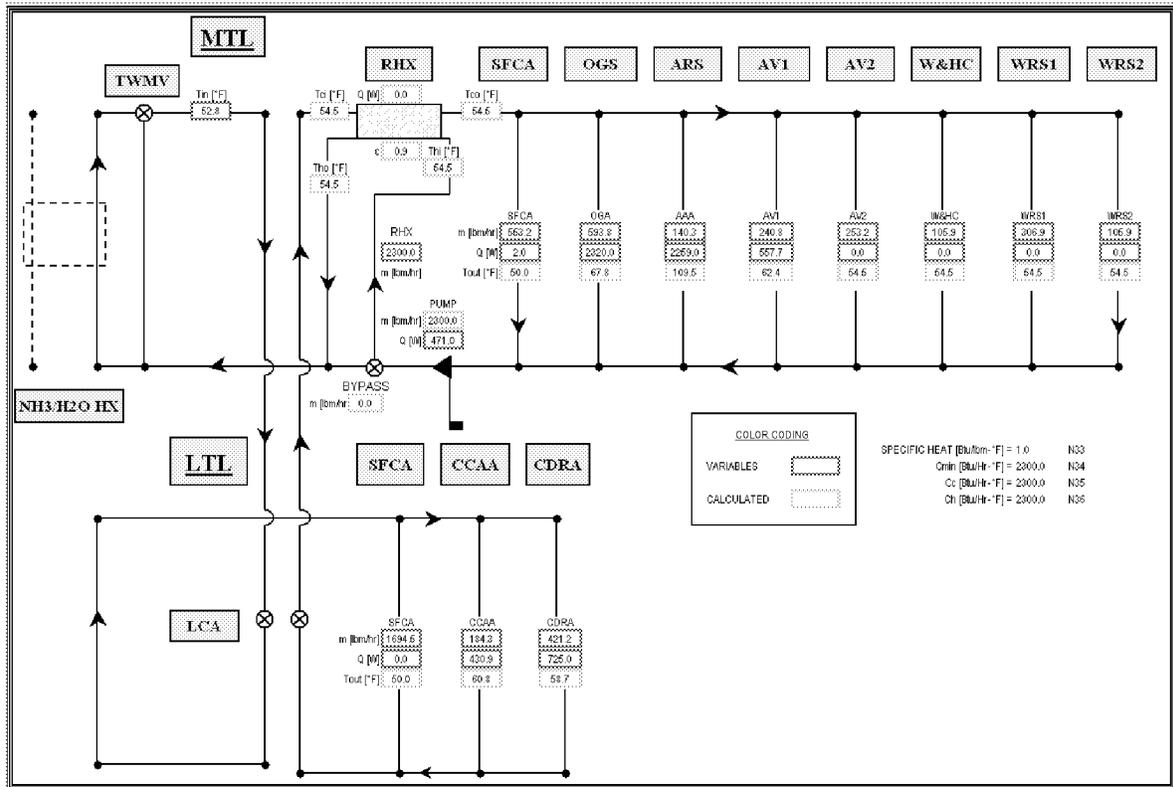


Figure 4 – Excel Spreadsheet Interface

The flow distribution in the parallel branches of the LTL was determined separately by the SINDA/FLUINT model. Details of this model are noted in the next section. Closed form results illustrate the RHX hotside flowrates corresponding to MTL and LTL injected heat loads which are required to maintain the RHX cold side exit temperature above the dew point (65.0°F). Trends show that the MTL heat load must increase when the LTL heat load is decreased. The boundary of acceptable performance is also shown, based on total flowrate of 2300 lbm/hr. Figure 5 shows the closed form solution.

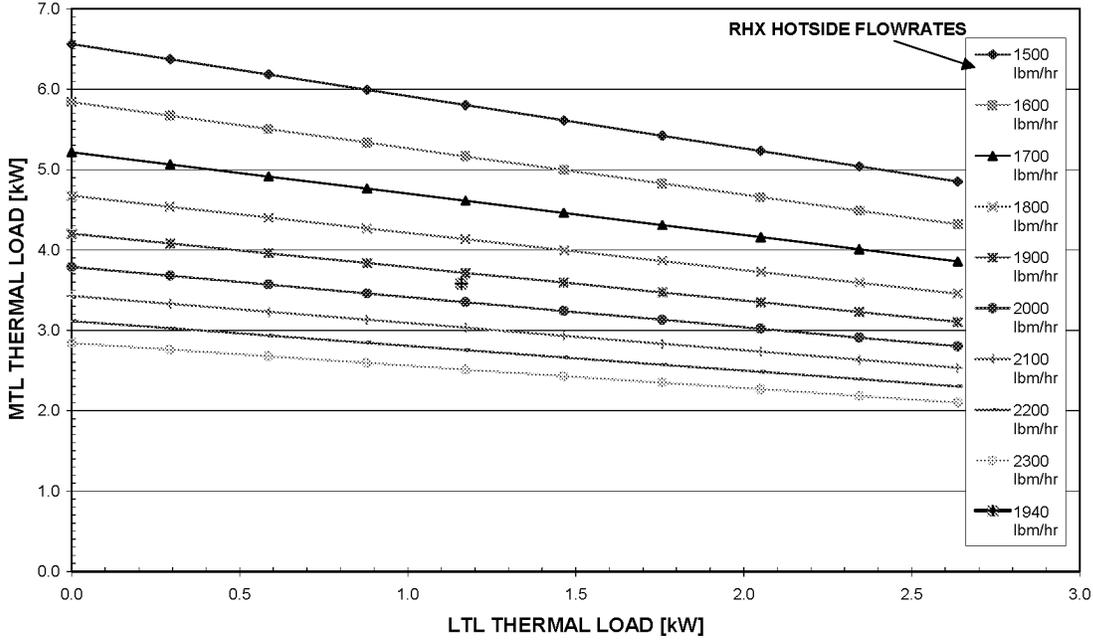


Figure 5 – Closed Form Results

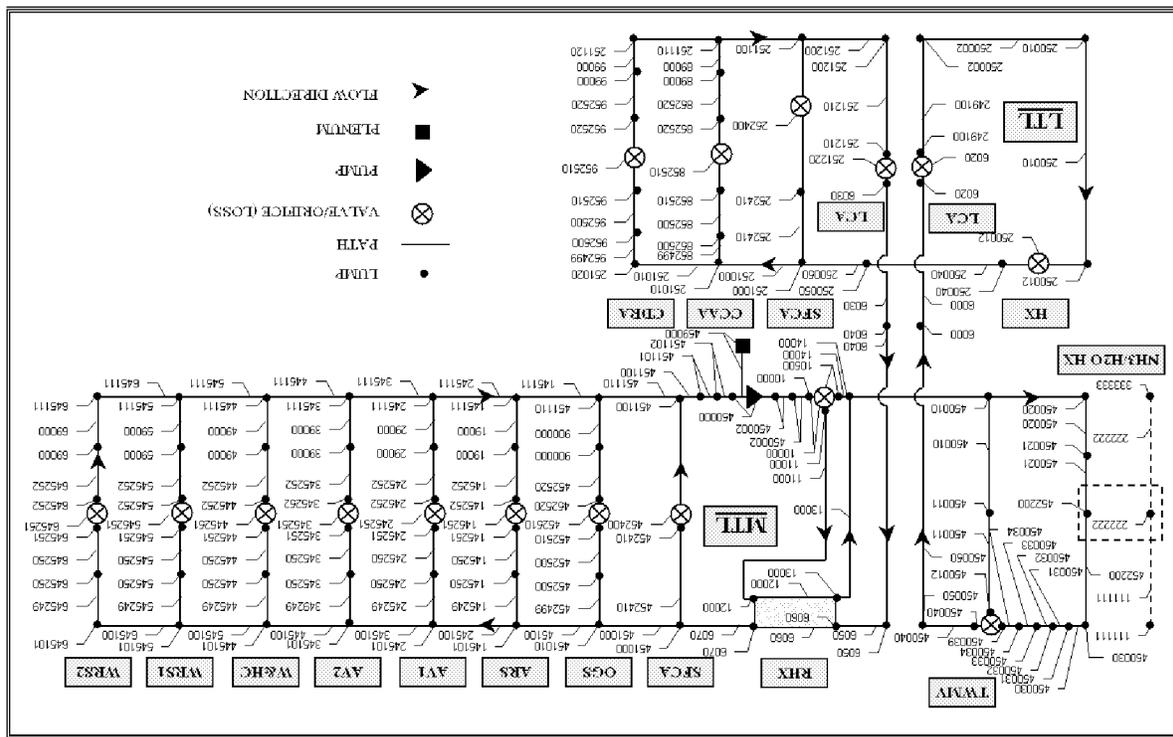
SINDA/FLUINT

A simplified SINDA/FLUINT mathematical model, representing the Node 3 single loop configuration (Node 3 core only, no resources provided to Node 1 Airlock or HAB), was developed to determine the RHX performance independent of the close form solutions. This model was based on the current Node 2 thermal/hydraulic model and incorporates common IATCS components' hydraulic characteristics as well as software control algorithms. Modifications were made to the Node 2 model to account for effects from additional racks, pipe lengths, MTL/LTL single loop configuration and RHX thermal/hydraulic performance parameters [2]. Figure 6 shows the SINDA/FLUINT model.

When compared, the trends of the SINDA/FLUINT and closed form solution differed only slightly due to the control algorithm software error band, which translates to a $\pm 5^\circ\text{F}$ tolerance, CTB MTL TWMV single mode set point of 47.5°F vs. 50.0°F , and RHX TWMV set point of 62.5°F vs. 65°F .

Additional modeling parameters of interest include racks, the LTL System Flow Control Assembly (SFCA) valve and the LTL CTB TWMV. The current plan is not to manipulate Manual Flow Control Valves (MFCV) during the failure; therefore, all rack simulated "LOSS" input values remained constant based on nominal design flowrates. A failure of power domain 2/3 or Loop B ammonia would result in the SFCA remaining in the last commanded position, which was assumed to be nominal. Therefore, the LTL SFCA valve coefficient was set to a constant based on the calculated value for the nominal LTL flowrate and a setpoint of 13 psid. The LTL CTB TWMV valve loss coefficient was set to a value corresponding to the full bypass condition. It was assumed that in case of the aforementioned failure, the TWMV would be manually set to this position. The MTL PPA was set to a constant flowrate of 2300 lbm/hr based on performance degradation from the nominal 3000 lbm/hr. Setpoints used in the analysis for the MTL CTB TWMV and RHX TWMV were 47.5°F and 62.5°F respectively, and a loop A ammonia inlet temperature of 40.0°F .

Figure 6 – Node 3 IATCS Math Model



CONCLUSION

This study was made to determine if the condensation preclusion requirement could be met while the TCS is in single loop mode under a “low load” scenario. Currently, the heat loads are not guaranteed accurate or final in the Node 3 design. This ambiguity makes it difficult to modify the more complex SINDA/FLUINT model. The closed form solution allows for a much timelier analysis and trade study capability without sacrificing accuracy.

REFERENCES (STYLE=PAPERHEADINGS)

1. Node 3 DR-1, Torino, Italy, July 1999
2. Allied Signal Aerospace Equipment Systems, Doc. No. 97-69186 pg. 3.3.2-4
3. Frank P. Incropera and David P. DeWitt, “Heat and Mass Transfer,” Chap.11, John Wiley & Sons, New York, 1996